

REPORT OF THE MODELING WORKSHOP  
ON YEAR-CLASS STRENGTH FORMATION OF RED KING CRAB



By

Albert V. Tyler and Gordon H. Kruse

Regional Information Report No. 5J95-11  
Alaska Department of Fish & Game  
Commercial Fisheries Management and Development Division  
P.O. Box 25526  
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## ABSTRACT

Drawing on the accumulated knowledge of red king crab biology, an exploratory model was developed to examine the effects of physical and biotic factors on year-class strength formation in Bristol Bay and Kodiak stocks. The model was developed by specifying life history stages that seemingly have varying rates of survival associated with environmental changes from year to year. Processes and stages incorporated into the model are development of fecundity, mating success, fertilization rate, hatching success, survival of zoea, glaucothoe larvae, juveniles, and adults. The model illuminates the kinds of data necessary for understanding the changes in year-class strength and age structure, and highlights key processes that lead to change.

## INTRODUCTION

A modeling workshop on recruitment of king crab was held at the Juneau Center, School of Fisheries and Ocean Sciences, May 18 and 19, 1994. It was attended by 14 people from Alaska Department of Fish and Game, National Marine Fisheries Service, and School of Fisheries and Ocean Sciences. The workshop was organized by Gordon Kruse and Al Tyler and sponsored by the Commercial Fisheries Management & Development Division, ADF&G.

Presentations were made on several subjects related to recruitment, including: Management concerns for king crab (Kruse), new length-based modeling of trends in year-class formation in Bristol Bay red king crab (Zheng), decadal scale changes in king crab recruitment, other biota, and physical factors (Tyler), decadal scale changes in ocean physics in the Bering Sea and Alaska Gyre (Niebauer), king crab larval survival and factors of influence (Shirley), changes in red king crab and associated species in Bristol Bay (Otto).

A conceptual structure for modeling was developed by Tyler, followed by a discussion of recruitment hypotheses within the model structure. The result was an intensive review of knowledge on mortality, growth and development of king crabs. In addition, a recent video was shown by Donaldson made while SCUBA diving on a king crab pod in the Kodiak area. Also, Zhou demonstrated mating of crabs in the laboratory.

The purpose of the workshop was to synthesize biotic and abiotic relationships that could influence year-class strength of king crab in selected populations. Recent research findings of ADF&G and NMFS may allow further development of statistical and simulation models of processes that influence king crab recruitment. To explore this possibility we invited a number of specialists to the modeling workshop. Minimally we wished to identify the kinds of data that are necessary to develop a better understanding for future work. If the data allowed we would develop a dynamics model that incorporated factors seeming to influence the development of year-class strength. This work would be carried out in the months to follow.

Activities during the workshop included:

- Framing a conceptual structure for modeling
- Identification of possible subject areas for recruitment hypotheses
- Detailed discussion on recruitment hypotheses for red king crab
- Consider data needs for research on these hypotheses
- Discussion on possibilities for computer modeling.

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## SUMMARIES OF INDIVIDUAL PRESENTATIONS

**Management concerns and potential fishing effects on Alaskan king crabs**

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Alaskan king crab stocks are managed on different harvest strategies depending on availability of abundance data and historical precedent: (1) **2-S** based primarily on minimum size and sex (males only); (2) **3-S** based on size, sex, and season (no fishing during mating and molting); (3) **fishery performance** in which harvest is managed on historic catches or inseason catch-per-unit-effort; and (4) **exploitation rate** in which a specified fraction of the exploitable biomass is harvested (Kruse 1993).

Red king crabs possess some attributes that render them prone to overfishing. They are highly aggregated so that high catch rates can be taken from dwindling stocks. They possess a high per unit value. For example, in recent years in the Bristol Bay fishery an average legal red king crab weighed about 6.7 pounds and received \$5.00/lb (Griffin and Ward 1994) for an exvessel value of \$33.50 per crab. Other biological features that render the species vulnerable to overharvest include longevity ( $t_{max} > 20$  yr), old age of maturity (7 yr), long periods between strong year classes, and complex reproductive strategies.

Kodiak and Bristol Bay populations of red king crabs provide well-documented examples of stock collapse. Population estimation with a measurement error model shows that total (fishing plus natural) mortality exceeded recruitment eight out of 10 years during the waning years (1973-1982) of the Kodiak fishery (Kruse 1986, 1987) as well as each year during 1979-1982 when the Bristol Bay stock crashed (Kruse and Collie 1991). Model estimates of legal harvest rates in Bristol Bay were generally 20-40% during 1974-1990 with the exception of 70-75% in 1980-1981 during the crash. For the Kodiak stock, harvest rate increased steadily from 20% in 1973 to 85% in 1982 – the last year of the fishery. Periods of low recruitment were also coupled to the stock collapses in both areas. Although the cause of recruitment failures have not been clearly established, high harvest rates experienced just prior to these collapses are clearly not biologically sustainable.

Kruse (1993) reviewed additional sources of fishing mortality other than direct harvest: (1) ghost fishing by lost pots and nets; (2) bycatch in trawl fisheries; and (3) discards in the crab fisheries may cause mortality through lethal injuries, reduced growth, increased predation, egg loss, and limb loss.

Other effects of fishing on crab stocks may be more subtle (Kruse 1993). Current harvest strategies alter sex ratio and size structure that could adversely affect reproduction by: (1) reduced availability of suitable mates for females; (2) lowered male reproductive capacity because small males in fished stocks may not be able to fertilize full clutches of multiple females as can large males in unfished stocks; (3) old shell males of potentially high reproductive success do not accumulate in heavily fished stocks; (4) reduced age structure may eliminate a stock's natural buffer against infrequent strong year classes; and (5) genetic selection for slow growing crabs.

## **A length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska**

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A length-based population model generalized from Sullivan et al. (1990) was constructed for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. The model incorporates stochastic growth in which individual crabs molt from one length class to another according to a probability transition matrix, gradual recruitment over length, and a bowl-shaped pattern for instantaneous natural mortality as a function of length with high mortalities at both small and large sizes. A non-linear least squares approach was used to estimate abundance, recruitment, and natural mortality. The model was applied to abundance and catch data from 1968 to 1993. The observed population abundances were fitted well with a length-based model. Natural mortality was estimated to be 3 to 6 times higher in the early 1980s than during other periods. High natural mortality coupled with high harvest rates and followed by low spawning biomass may have contributed to the collapse of the population in the early 1980s and its continued lack of recovery. The stock-recruitment data estimated from the length-based model provided a good fit to both general and autocorrelated Ricker stock-recruitment models. The general Ricker model is supported by strong recruitment associated with intermediate levels of spawning biomass and extremely low recruitment related to low spawning stock, while the autocorrelated Ricker model fitted the data slightly better and is supported by the fact that extremely strong and weak recruitment occurred successively over two separate periods.

## **Development of a hypothesis relating changes in year-class strength to ocean climate**

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Three analyses have been carried out regarding stock and recruitment relationships in red king crab. The study by Reeves (1990) shows that a reasonable relationship between stock and year-class strength can be constructed for the Bristol Bay stock of red king crab for the years 1968 through 1979. High levels of year-class strength were noticeable for the years 1968 through 1970, 1972, and 1974 through 1976. Low recruitment occurred in 1971, 1973, and 1977 through 1979. For the dome-shaped relationship between stock and recruitment the peak recruitment rate occurred in the range of 15 million to 40 million female spawners.

Zheng et al. (In press) in their analysis of year-class strength in the Bristol Bay stock showed high recruitment (greater than 1.32 billion per year age-7 crabs both sexes) occurred 1966, 1967, 1968\*, 1969\*, 1970\*, 1971, and in 1973, and 1975\*. The symbol\* shows coincidence of high recruitment with Reeves' study. Low recruitment occurred in 1976, 1977\*\*, 1978\*\*, 1979\*\*, and 1980 though 1986. The symbols\*\* show coincidence of low recruitment with Reeves' study. Thus, through a period of



overlap of 11 years for the two areas, there were 7 synchronies, indicating a basic consistency in the studies.

Another study of red king crab year-class strength was carried out for the Kodiak stock (Schmidt et al. 1992). In a series going from 1972 through and including 1985, only 1972 and 1973 were years of high year-class strength. The 1972 year class was not indicated as strong in either Bristol Bay study, but 1973 was a strong year in Zheng's study. In all three studies, only low recruitment occurred since 1976. These similarities are a suggestion that wide-spread extrinsic events occurred thereby bringing on synchronous high or low recruitment in the two areas.

High year-class strengths came during a period of intermediate spawning-stock sizes of 25, 000 to 50, 000 tonnes, leading Zheng et al. to look for and find a reasonable fit to a dome-shaped Ricker stock and recruit model. They noted the continued low recruitment since 1976 and proposed the possibility that oceanographic factors might be influencing the formation of more recent small year classes. Post-1976 recruitment is always less than pre-1976 recruitment except for the 1972 year class, which is low. A tenable alternative hypothesis is that a high production period shifted to a low production period due to non-density dependent factors of a physical oceanographic nature.

There is evidence from other sources that a strong climatic change occurred in the mid-1970s that influenced ocean dynamics and biological productivity. In the central north Pacific Ocean there was a strong increase in the abundance of copepods in 1974 through 1977, with continued good levels into 1980. These data were reported from the Ocean Station P data series along with a new index of the Aleutian low pressure zone from 1965 to 1980 (Beamish and Bouillon 1993). The intensity of the winter low pressure changed in parallel to the copepod index. The deepening of the Aleutian Low is usually associated with warm coastal waters and high sea level (Emery and Hamilton 1985, Roden 1989). Another data series shows that the average pressure in an area 27.5° N to 72.5° N; and 147.5° E to 122.5° W was 1010.8 mb from 1976 to 1988; down from an average of 1012.9 mb, 1946 through 1975 (Pearcy 1992). In addition sea surface temperature and temperature at depth showed an unusually strong and rapid increase in 1977 and 1978 in the northern Gulf of Alaska off Seward (Royer 1989) as well as off Kodiak and Bristol Bay (Rogers 1984).

It is well known that several groundfish stocks in the eastern Bering Sea showed a strong change during the decade starting in 1977 or 1979 (Bakkala 1993). Greenland turbot biomass showed rapid decreases from approximately 120,000 t to 10000 t. Pacific cod showed a 600% increase to about 1.1 million tonnes, while rock sole showed about a 350% increase. Other species showing a pronounced increase were yellowfin sole, flathead sole, Alaska plaice, arrowtooth flounder and mixed skate species. Gulf of Alaska pollock showed strong increases in recruitment rate in the late 1970s, while Bering Sea pollock were variable in recruitment changes, but with strong recruitment in 1978, 1982 and 1984. Pacific herring showed strong and regular recruitment increases following 1976 in the eastern Bering Sea and in various localities in the Gulf of Alaska, including Prince William Sound (Fritz et al. 1993).

It is clear that in the North Pacific and in the Eastern Bering Sea multiple and major changes have occurred in the productivity of the waters in the late 1970s. The period of high recruitment of the 1960s and early 1970s led to the high biomass of red king crab that made possible the major fishery of the late 1970s and early 1980s. This high

recruitment level did not pass unchanged into the new oceanographic regime following the climate shift. That the change in productivity of king crabs was due to oceanic climate change seems likely, but is not proven. This hypothesis by no means discounts the density-dependent relationship proposed by Reeves and Zheng et al., with a critical stock-size below which the small size of the spawning stock interferes with recruitment productivity.

## **Decadal scale changes in ocean physics in the Bering Sea and Alaska Gyre**

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Strong shifts in atmospheric measures occurred during the late 1970s that resulted in warmer winter conditions that continued through the early 1980s. Shifts in temperature in the Bering Sea seem related to the location and intensity of the Aleutian low pressure cell. In the Gulf of Alaska the periods of warm ocean condition appear to be associated with an eastward displacement and intensification of the Aleutian low and downwelling in coastal waters. Recent work by Trenberth and Hurrell (1994) suggests that the entire period 1977 to 1988 differs markedly from the 1946 - 1976 and 1989 - 1992 periods. The Aleutian Low was more intensive than normal in the 1977 though 1988.

Several of the measures can be related to the decadal scale of changes that are important to biological oceanography (Niebauer 1988). Percentage of ice cover has changed from the 1970s through the 1990s. One can get weekly ice cover charts from NOAA and measure the percentage of ice cover with a planimeter. Also there is a long record of sea surface temperature (SST) from ship of opportunity data taken with a square centered on the Pribilof Islands. The newer part of the time series is from satellite charts. Air temperature is taken from the Pribilof Island Airport, and a wind direction time series from the airport is expressed from wind components from the north and south.

The major driving factors for these variables are the changes in the position and intensity of the Aleutian low. Changes in this low pressure system are linked to the El Nino- Southern Oscillation event (ENSO) that originates in the south Pacific. The index of change, called the Southern Oscillation Index (SOI), is measured as the difference in sea level atmospheric pressure between Tahiti (a high pressure area) and Darwin, Australia ( a low pressure area) (Niebauer 1983, Hamilton 1988).

One can compare the changes in the Bering Sea SST, ice cover, air temperature, and N/S wind to the changes in the SOI. Using linear regression thirty percent of the variability in the Bering Sea variables are explained by the ENSO changes (Niebauer 1988). There are periods of warm that can be thought of as El Nino periods and cold periods that can be thought of as anti-El Nino periods. During cold periods the Aleutian low is minimal and to the west. During the warm periods the low is strong and to the east.

In the mid-1970s, the ENSO event coincided with a change in the 18 year lunar tide-cycle that is related to sea temperature in the Gulf of Alaska (Royer 1993). Royer has developed a time series of CTD casts at the mouth of Resurrection Bay in the northern Gulf of Alaska going back to the early 1970s. This series indicates that an 18 year temperature cycle at depth that is correlated to the tidal (lunar) cycle of this same period (Royer 1993). In the mid-1970s the ENSO event, was coincident with the high temperature period of the 18 year cycle. The two events moving together caused unusually warm water.

### **Larval survival of red king crab**

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By sampling larvae in Auke Bay (SE Alaska) we have shown that there is a close timing between the chlorophyll maximum and the incidence of first stage red king crab zoeae in the plankton (Shirley and Shirley, 1989; 1990b). The maximum density of both usually occurs during the same week. The early zoeal stages are phytoplanktivorous and prefer the diatom *Thalassiosira*, which is an early successional species in the spring phytoplankton bloom (Shirley and Shirley, 1989, 1990a; Paul et al. 1989; Paul et al. 1990). When ovigerous female red king crabs were cultured at the Duke Marine Lab on the Atlantic Ocean, their eggs never hatched even though the embryos were apparently healthy and in late developmental stages (unpublished observations, T. Shirley). Similarly, embryos incubated in a series of temperatures higher than normal in laboratory experiments in Auke Bay had delayed hatching, even though they had reached the final stages of development months earlier (Shirley et al. 1990c). Embryos incubated at much colder temperatures developed normally but much slower and also did not hatch when they reached final developmental stages in the fall months. One hypothesis is that the embryos may require some environmental cue, perhaps phytoplankton exudates, to elicit hatching (T. Shirley, unpublished observations).

Hatching in the field in Auke Bay extended from late February through May during a five year study, but peak hatching occurred in late April (Shirley and Shirley, 1989a; 1990a,c). The midpoint of hatching (evident from first zoeal stages in the plankton) was significantly correlated with seawater temperatures recorded during the incubation period. In laboratory experiments, smaller, primiparous females (those with their first brood) hatched their eggs earlier in the season than did larger, multiparous females; a significant relationship was found between female size and hatching time (Shirley and Shirley, 1990c). Field tracking studies of ovigerous females supported the laboratory observations (Stone et al. 1992, 1993). In plankton studies, the duration of the larval period was significantly correlated with chlorophyll standing stock, with shorter larval periods occurring in years with higher chlorophyll production. Years with longer larval periods had lower larval survival. The best fit for larval survival data included both sea water temperature and primary production; highest survival occurred when higher temperatures co-occurred with higher food concentrations (Shirley and Shirley 1990b; T. Shirley, unpublished data).

In the laboratory, females mated with any size male. If several males were present, the largest male mated with the female. If a female did not mate, egg extrusion was delayed and often did not occur. An unresolved question is whether or not eggs that are not extruded are resorbed by the female, and whether this delays or inhibits mating activities the following year. Unfertilized eggs that were extruded by females dropped off the pleopods within a few days. Females mated with small males that had recently mated, produced egg clutches that were only partially fertilized.

## DEVELOPMENT OF AN EVENTS-TIME TABLE OF HYPOTHESES

### Introductory remarks

The second day of the workshop was devoted to developing a stage by stage description of the life history events for red king crab, including the location and timing of the life stages, plus the coincident physical oceanographic and biological events that could influence the productivity and survival rate of the stages. The result was a series of hypotheses related to year-class strength. The table that was developed has been laid out at the back of this section. This approach to model development may be called the Events-Time Procedure (Tyler 1992). The group made comments on crab stocks in Southeast Alaska, Kodiak and Bristol Bay. In this write-up we focused on Kodiak and Bristol Bay because the time series were longest there and so would lend themselves better to the modeling work. The statements and hypotheses that follow here about biological relationships were all contributed by the workshop participants.

### 1. Fecundity

The first stage and activity considered was the development of the egg clutch inside the female. It was suggested that factors that influence general tissue elaboration and growth would also influence clutch development. It was pointed out that at times the eggs do not develop, and a mature female may molt without producing eggs, i.e. that barrenness is sometimes observed (McMullen and Yoshihara 1971). It was suggested that this phenomenon may be related to the age of the crab and may be an expression of senescence. Females are generally in 30 to 200 m of water during the major part of the year when the eggs develop, in months July to January. It was stated that fecundity is related to female crab size and does not exceed 500,000 eggs (Otto et al. 1990). But fecundity also increases with the number of spawnings, or reproductive history, and so is also related to age. It is speculated that a molt may be skipped by the female, and when this occurs eggs may not be developed that year. Fecundity likely depends on rations and temperature. Warmer years may decrease fecundity as may exceptionally cold years. There is likely a critical level of degree-day accumulation before eggs are brought to full maturation and are ready to be fertilized.

### 2. Mating and Fertilization

Egg fertilization takes place at depths of 20 to 100 m from March through April off Kodiak, and February thorough June in Bristol Bay. Females and males are sometimes distributed in their own patterns and so at times there may not be enough males for all females, i.e., the sex ratio in a given locality may be dominated by females. Timing in mating depends on the reproductive history of the female. Females that have not mated before (primiparous) mate earlier than multiparous individuals (Shirley and Shirley 1990c, 1989). Mating occurs earlier in warmer years. The first female that a male mates with tends to have a greater percentage of eggs fertilized than the last female he mates with (Paul and Paul 1990). Percentage fertilization is increased when a female mates with a larger male (Paul and Paul 1990). After eggs

are fertilized, egg parasites and disease may cause egg mortality and it is speculated that warmer water may increase the egg mortality rate (Kuris et al. 1991).

### 3. Hatch timing

Hatching occurs in waters 20 to 200 m depth, in March through April in Kodiak, and in April through June in Bristol Bay. Hatching is well timed with the chlorophyll maximum, and perhaps needs a water quality cue linked to the diatom genus *Thalassiosira* (T. Shirley, unpublished). Egg maturation depends on degree-days accumulated when eggs are incubated in the 2 to 5°C range (Shirley and Shirley 1988).

### 4. Percentage successful hatch

Warm ambient temperature decreases percentage successful hatch. At 28 C larvae are not viable.

### 5. Larval survival I (zoea stages)

Zoea tend to be in the water column at depths of 100 m or less. They are found during the months of March through June off Kodiak and from April through August in Bristol Bay. High concentrations of diatoms are needed to prevent starvation of the larvae (Paul et al. 1989, Paul and Paul 1990). In Bristol Bay, winds can cause convergence, and possibly concentration of larvae and their food species. Fast tidal currents of 40 to 50 cm/sec may be a factor influencing larval survival, with tidal mixing being important for primary production. The non-tidal drift is only 3 - 5 cm/sec. Thick cloud cover for extensive periods of time can delay the development of a peak in chlorophyll concentration, and perhaps even result in lower concentrations when the peak occurs. High levels of first sea-year juvenile sockeye salmon may decrease survival through predation.

### 6. Larval settling (glaucothoe stage)

Glaucothoe larvae settle in rocky habitat at depths of 0 to 50 m, "choosing" boulders and rocks (Armstrong et al. 1993, Powell and Nickerson 1965) that often have large attached forms such as hydroids, ectoproc, hydroids and soft coral. Settling occurs in May through July in Kodiak and June through August in Bristol Bay. Because this habitat is considered to be obligatory, currents that move the larvae away from this habitat prior to settling would decrease the survival rate. The settled larvae are cannibalistic (Broderson et al. 1990), and so at higher densities of settled larvae there would be higher mortality rates. This cannibalism would lead to density dependent mortality rates. As the population decreased so would the density dependent mortality rate. This stage would contribute to population stability.

### 7. Juveniles. Age 1 to 6

As the crabs age they are found in progressively deeper water. Age-1 are found in 0 - 60 m, while age-6 tend to be in 20 to 100 m (Stone et al. 1993, Powell and Nickerson 1965, Dew 1990, Armstrong et al. 1993). (Note: some age-5 crabs would be mature). Years with higher temperatures would give higher molt frequencies and greater size at age (Stevens and Monk 1990, Stevens 1990). Females grow more slowly than do males (Wallace et al. 1949). Food competition is likely with some of the flatfish species that have shown biomass increase in the 1980s. Competition would likely decrease growth rate. Smaller crabs are likely subject to higher predation rates by Pacific cod and sculpins. Also molting crabs are subject to predation by cod (Livingston 1989). Pacific cod increased their abundance in the 1980s. Sea otters are also predators of king crab (Rotterman and Simon-Jackson 1988).

**8. Mature stages. Age 5 to 15 .**

Longevity may be as much as 20 years. Mature females generally continue to molt and spawn every year (Powell 1967, McMullen and Yoshihara 1971), but grow more slowly than males. Individuals that have molted recently are subject to predation mortality. Since males protect recently molted females, there may be higher predation mortality rates when the ratio of females to males is locally high.

STAGE / ACTIVITY	LOCATION / DEPTH		MONTHS		OCEANOGRAPHIC HYPOTHESES	BIOLOGICAL HYPOTHESES
	K	BB	K	BB		
1. Fecundity-development of egg clutch vs barrenness. Generally 0 to 350 K eggs / female.	30 - 200 m	Same	both 7 - 1		<ul style="list-style-type: none"> <li>-warm water may give an increase in egg mortality due to development of parasites and disease.</li> <li>-there is a critical level of degree-day accumulation for full maturation</li> <li>- very cold temp may delay maturation of eggs to biennial spawning</li> <li>-maximum fecundity may depend on an optimum temp.</li> </ul>	<ul style="list-style-type: none"> <li>- fecundity is related to crab size</li> <li>- higher fecundity is linked to number of previous spawnings</li> <li>- senescence is possible in older animals</li> <li>- a molt may be skipped if egg development is delayed and eggs are resorbed</li> <li>- fecundity may depend on rations</li> <li>- parasites and pathogens may cause reduction of fecundity or sterility</li> </ul>
2. Mating and egg fertilization	20 - 100 m		3-4 2-6		-	<ul style="list-style-type: none"> <li>- fertilization rate is higher with larger males</li> <li>- the first female mated gets more sperm than does last female mated by one male.</li> <li>- female's aggregate, but males not always distributed in the same way as females.</li> <li>- Timing of mating depends on female's previous reproductive history as well as the water temperature.</li> </ul>
3. Hatch timing	20 - 200 m		3-4, 4-6		<ul style="list-style-type: none"> <li>- For the temp range 2 - 5 C egg development time depends on accum. degree-days</li> </ul>	<ul style="list-style-type: none"> <li>- Primiparous spawners hatch eggs, then multiparous crabs</li> <li>- Need a water quality cue, perhaps from the diatom <u>Thalassiosira</u></li> </ul>
4. Percentage successful hatch	-		-		<ul style="list-style-type: none"> <li>- at 28 C &amp; higher larvae are not viable. There is a temperature level optimizing % viable hatch</li> </ul>	<ul style="list-style-type: none"> <li>- parasites (<u>Carcino</u> <u>nemertes</u>) may reduce fecundity</li> </ul>

STAGE / ACTIVITY	LOCATION / DEPTH		MONTHS		OCEANOGRAPHIC HYPOTHESES	BIOLOGICAL HYPOTHESES
	K	BB	K	BB		
5. Larval survival (zoea)	<100 m		3-6	4-8	<ul style="list-style-type: none"> <li>- Bristol Bay - Mixing due to high tidal currents of 40 - 50 cm/sec increases productivity; low non-tidal currents of only 3 - 5 cm/sec.</li> <li>- Wind from south can cause Ekman transport into Bristol Bay.</li> <li>- A lack of solar energy due to heavy cloud cover can delay the peak chlorophyll concentrations by 5 - 7 days.</li> </ul>	<ul style="list-style-type: none"> <li>- High concentrations of specific, concentric diatoms are needed, or starvation can result in 4 days.</li> <li>- Predation is by pollock, salmon, T. raschii</li> <li>- Diel vertical migration may be a retention mechanism</li> </ul>
6. Settling larvae (glaucothoe)	0 - 50 m, on active bottom with sediments of rock, shell, boulder, often with a complex of high relief organisms like soft coral,		5-7,	6-8	<ul style="list-style-type: none"> <li>- Currents that move larvae away from the required habitat can increase larval mortality. Habitat seems obligatory.</li> </ul>	<ul style="list-style-type: none"> <li>- Cannibalistic nature of settled larvae leads to density dependent mortality.</li> <li>- Predation by sea stars, pycnopodia</li> </ul>
7. Juveniles. Age-1 to 6. Note, some age 5 crabs are likely mature.	age-1, 0-60 m	age-6, 20-100 m	-		<ul style="list-style-type: none"> <li>- Increased temperature gives increased molt frequency and size at age.</li> </ul>	<ul style="list-style-type: none"> <li>- Depth of habitat increases with age.</li> <li>- Food competition is likely with some flatfish species with major biomass increases in the 1980's.</li> <li>- Predation by Pacific cod, sole spp and sculpins include appendages of large molting crabs and whole crabs in smaller instars.</li> <li>- Sea otters are major predators</li> </ul>
8. Mature stages. Ages 5 to 15 (possibly older)	-		-		<ul style="list-style-type: none"> <li>- Molting frequency of males may drop as stock size decreases</li> </ul>	<ul style="list-style-type: none"> <li>- females grow more slowly than males.</li> <li>- Mature females are obligate spawners, molters subject to more predation if ratio males to females is decreased</li> </ul>



## CONCLUSIONS

It is not certain at this time whether we will be able to develop a computerized model from the data available on Bristol Bay red king crab. We would like to put together an exploratory model that expresses the relationships and hypotheses that seem relevant to a set of recruitment questions. The data and information on processes surrounding the formation of year-class strength for red king crab is well developed from many years of research by many people. We were able to express a number of well founded critical hypotheses regarding these processes as they apply to several stages of development from egg to adult.

We discussed four phases in the construction of the model.

a. Conceptualization

1. Development of hypotheses
2. Development of functional relationships
3. Development of logical structure

b. Computerization

1. Programming into a desktop computer
2. Carry out a series of simulated time runs by experimenting with variables and parameters within the model.

c. Validation - Comparing simulated output against real data series.

d. Conclusions

1. What insights are gained about the dynamics of recruitment?
2. What insights are gained about the present state of knowledge on king crab recruitment?
3. What are the missing critical data for advancement in our understanding?

At present we are at the Conceptualization Stage mentioned above. The Events-Time Table that we developed contains numerous hypotheses. We also have the beginning of a logical structure (Figure 1, 2) connecting these hypotheses. From the hypotheses it is clear that a number of functional relationships can be constructed between pairs of variables. These are the linear or curvilinear functions that relate one variable to another. We will begin researching existing information on these relationships. This research will result in a conceptual model. An attempt will be made to computerize the model.

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## MAIN RECRUITMENT MODEL

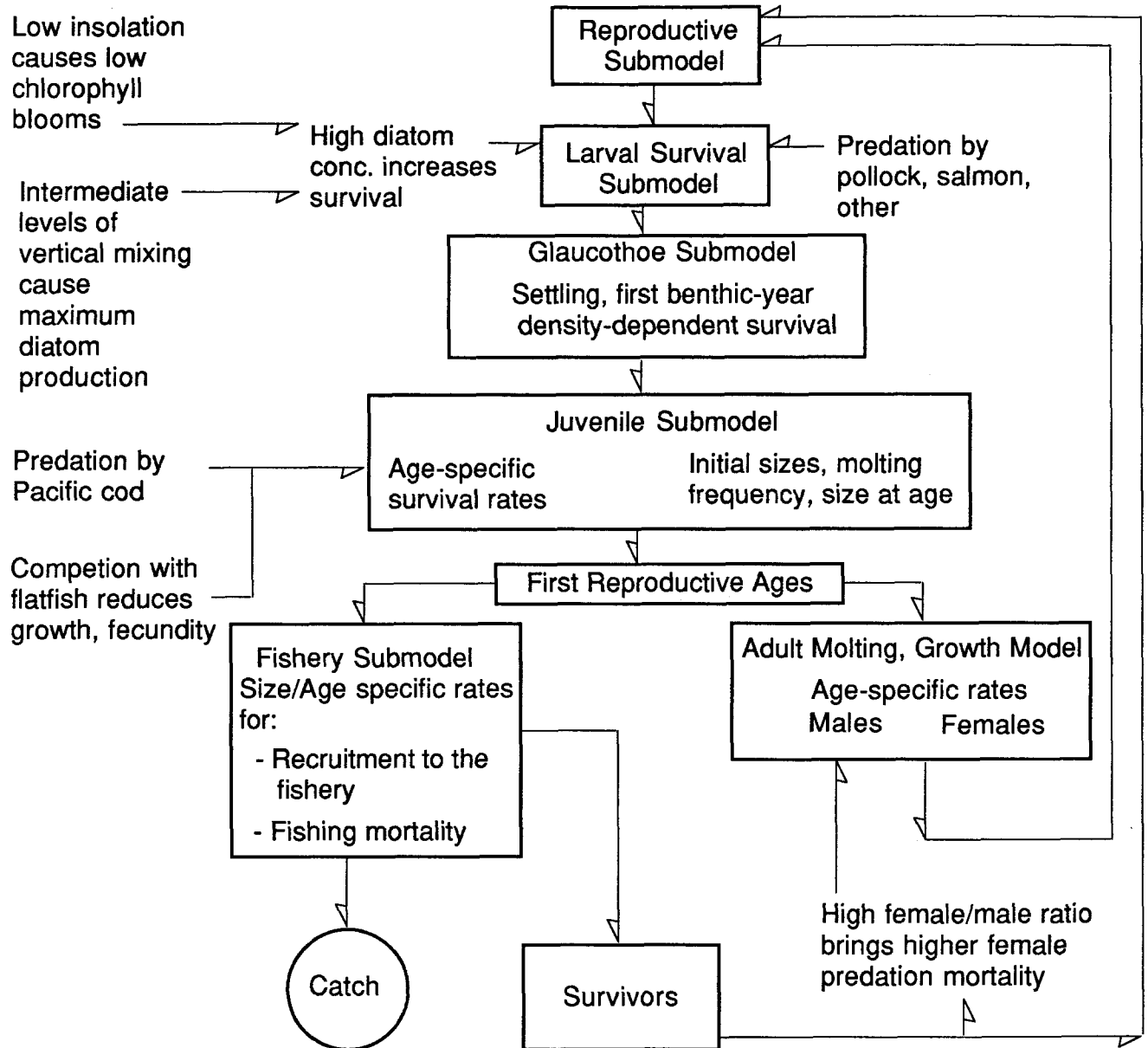


Figure 1. Flow chart of the cycle of modeled hypothetical relationships that lead to the formation of year-class strength in red king crab. The model is passed through once for each annual iteration. The variables of the central flow in boxes are influenced by relationships described to the sides of the chart. The logical flow starts with Reproduction Submodel and follows through to adult survivors.

# REPRODUCTIVE SUBMODEL

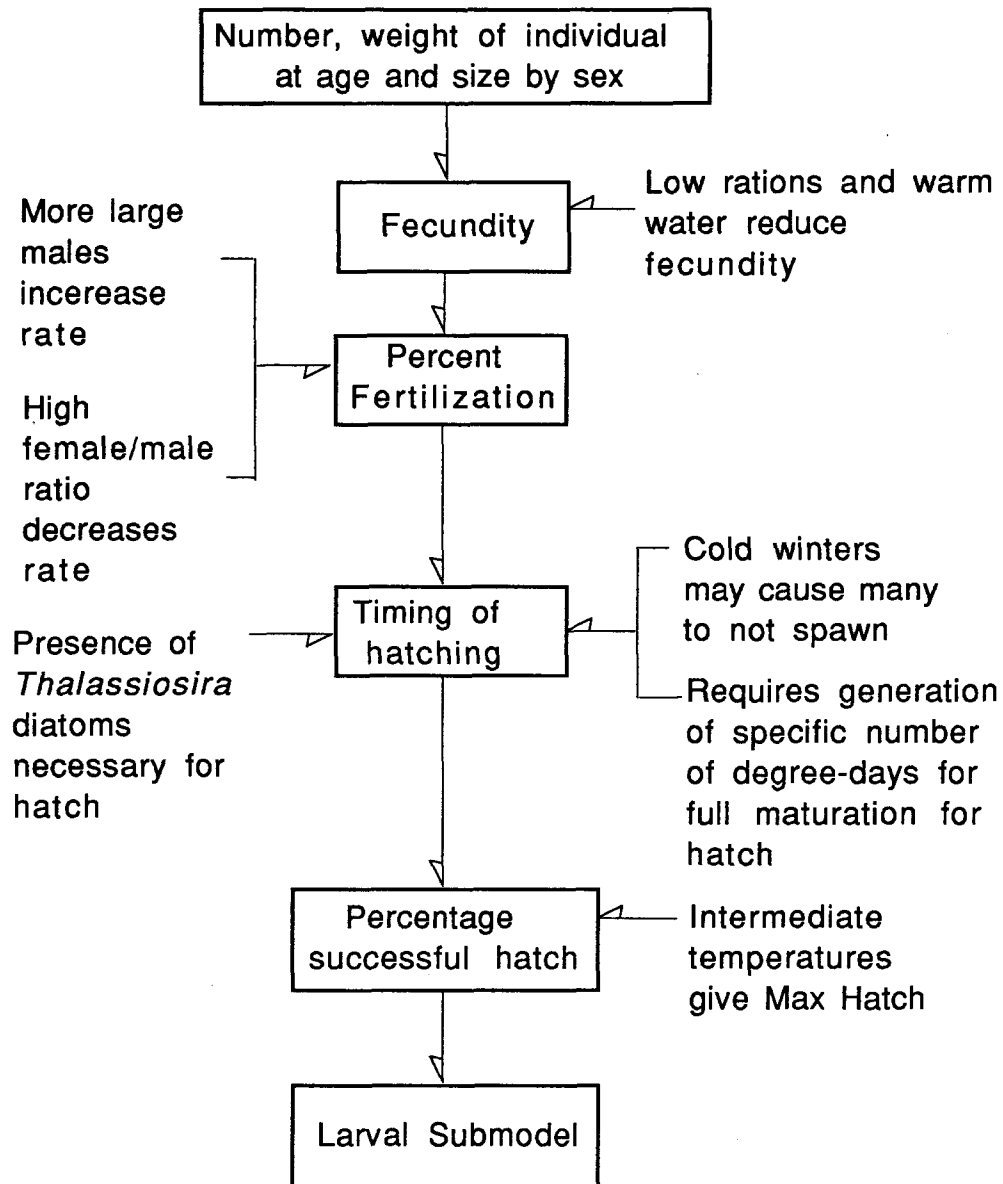


Figure 2. Flow chart for the annual Reproduction Submodel of hypotheses for year-class strength formation. The model is passed through once for each annual iteration. The variables of the central flow in boxes are influenced by relationships described to the sides of the chart.

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